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Multiple early to middle Pleistocene East Antarctic Ice Sheet variations in the Ricker Hills

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Summary Timing and amplitude of Antarctic ice level changes as response to past climate fluctuations are a major issue in paleoclimatology. In this study, we determined surface exposure ages with in situ produced cosmogenic nuclides (^{10}Be, ^{21}Ne) of four erratic boulders from a pre-last glacial deposit in the Ricker Hills, southern Victoria Land, located at the boundary of the East Antarctic Ice Sheet. The investigated area is not affected by alpine glaciers. Thus its glacial features and deposits are a direct proof of past ice sheet variations. Consistent neon and beryllium exposure ages indicate two major ice advances, one at about 1.4 Ma and another one around 1.0 Ma before present. Evidence for a third glacial event comes from an erratic boulder that was intermittently buried by cold-based ice. From our data we infer an upper age limit for this third event at around 665 ka.

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Introduction

The increasing interest in climate change and its impact on earth has heightened the need for paleoclimate records to predict future global environmental change. Continuous paleoclimate information derives from marine-sediments (Imbrie et al., 1993; Lisiecki and Raymo, 2005) and ice-cores (EPICA members, 2004; Petit et al., 1999). But the glacial record – although discontinuous – yields the most obvious evidence of past climate change. An ice advance or retreat is not simply temperature-related but reflects a dynamic response to more complex climate fluctuations, taking temperature and precipitation into account. Mapping and dating of the paleoglacial record is, therefore, an important issue for the understanding of paleoclimate.

Among the key sites for reconstructing the glacial response to past climate change are the presently ice-free areas of Antarctica. Glacial features of several ice sheet expansions are recorded in these regions (Baroni and Orombelli, 1987; Denton et al., 1984), and preserved over millions of years (Schäfer et al., 1999). Most surface exposure dating studies in Antarctica, using in situ produced terrestrial cosmogenic nuclides (TCN), come from the Dry Valleys area, focusing on million years old glacial landscapes (e.g., Brook et al., 1995; Bruno et al., 1997). During the last years, younger glacial chronologies, within (Staiger et al., 2006) and outside of the Dry Valleys (Fink et al., 2006; Oberholzer et al., 2003; Sugden et al., 2005), were investigated with TCN.

However, the previously mentioned studies depend on local conditions, as they come from coastal areas, where glacial deposits are generally related to outlet glaciers. Furthermore, some work is confined to Late Pleistocene and Holocene deglaciation chronologies. Therefore, surface exposure ages from Early to Mid-Pleistocene glacial features are still rare in Antarctica. When and to what extent major Antarctic ice level changes occurred prior to the Last Glacial Maximum (LGM) remains an open question. By dating erratic boulders of a pre-LGM drift with in situ produced ^{10}Be and ^{21}Ne in the Ricker Hills nunatak, southern Victoria Land, we directly date East Antarctic Ice Sheet (EAIS) variations. Thus, we supply another piece of information needed to complete the picture of how the EAIS reacted to Pleistocene climate change.

Geological setting

The Ricker Hills area is located in the southwestern part of the nearly N–S striking Prince Albert Mountains in Victoria Land (Figure 1). At the boundary of the EAIS, about 100 km from the western margin of the Ross Sea, the Ricker Hills represent a nunatak in the David Glacier system. With an area of 214,300 km^2, the E–W flowing David Glacier is one of the large glaciers, draining Dome C with an annual outflow of 15.6 km^3 (Rignot and Thomas, 2002). Ice flow around the Ricker Hills is generally SW–NE, but ice flow in an opposite direction occurs in depressions at the lee side of the nunatak. Present-day ice levels in the up- and downcurrent parts of the nunatak are ~1750 m and ~1100 m above sea level, respectively. The ice-free areas themselves extend from ~900 m up to 1830 m above sea level (Figure 2). They consist largely of Ferrar dolerites and to a minor extent of sediments from the Beacon Supergroup, overlying the Granite Harbour igneous complex. Very rare in the Ricker Hills are isolated outcrops of Kirkpatrick basalts (Capponi et al., 1999).

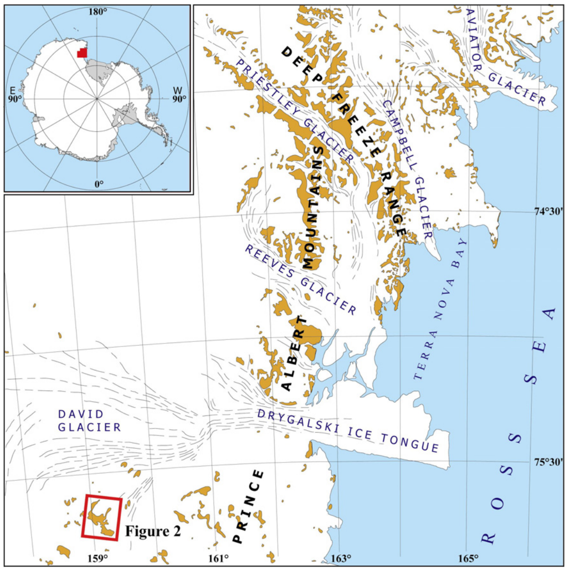

Figure 1. Overview map of Victoria Land, Antarctica. Inset shows location of Figure 2.

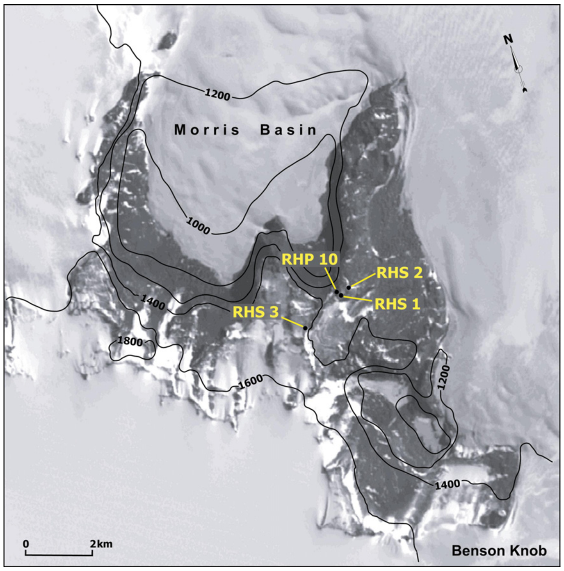

Figure 2. Satellite image of the Ricker Hills with sampling sites.

Geomorphological and glacial geological surveys of the Ricker Hills allowed us to distinguish at least five glacial drifts hereafter informally named RH 1 to RH 5 (Baroni et al., 2007). RH 1 and RH 2 represent the youngest glacial drifts deposited during the Holocene and Late Glacial, respectively. They are characterised by ice-cored moraines and hummocky deposits around the current ice margin and in the area of former ice lobes, where ice entered the nunatak depressions. Glacial sediments related to the LGM ice level change occur at higher elevations, sometimes with well defined moraine ridges, and are called RH 3, while RH 4 indicates an older Pleistocene drift deposit. Yellowish-red or red staining of boulder surfaces are typical for RH 4 deposits, and clearly differ from the grey colour of younger drifts. Scattered erratic boulders of RH 4 occur up to the top of the hills. The oldest unit in the relative stratigraphy is the Ricker Hills Tillite (RH 5), a lithified diamicton, which can be correlated to the more than five million years old sediments of the Sirius Group further south (Baroni and Fasano, 2006).

Cosmogenic nuclide exposure ages

In order to determine surface exposure ages of the RH 4 drift, we sampled four erratic boulders for TCN analyses. All boulders lie clearly beyond the RH 3 drift and were deposited by a pre-LGM ice lobe entering a nunatak depression from the northwest. Locations of the samples are indicated on Figure 2 and specific information is given in Table 1. To benefit from the multiple nuclide analyses (^{10}Be, ^{21}Ne) that are possible in quartz, we focused on quartz-bearing rocks. Except RHS 2, a quartzite sample, the collected material was obtained from Beacon sandstone boulders. Sample preparation was done according to the standard procedure of Kohl and Nishiizumi (1992). A split of each quartz separate was then kept for noble gas analyses, while the rest underwent further procedural steps following Ochs and Ivy-Ochs (1997) for beryllium extraction. Radionuclide measurements were carried out at the AMS facility of PSI/ETH Zurich (Synal et al., 1997). Noble gas concentrations were measured in ~50 mg quartz at the noble gas laboratories at ETH Zurich, using a non-commercial ultra-high sensitivity mass spectrometer equipped with a compressor source (Baur, 1999). Samples loaded into this unique noble gas mass spectrometer were degassed at 600, 800, and 1750 °C to separate the cosmogenic from the non-cosmogenic neon components.

Table 1. Site details.

Sample	Altitude (m asl)	a-b-c axes[a] (cm)	Correction factor
RHS 1	1438	160-90-150	0.962
RHS 2	1455	110-70-75	0.975
RHS 3	1589	220-100-70	0.962
RHP 10	1435	100-80-50	0.999

[a] Size of a-b-c axes for whole erratic boulder

Calculations of surface exposure ages were done with CosmoCalc (Vermeesch, 2007) and are based on sea level high latitude production rates in quartz of 5.1 at/g/y (Stone, 2000) for cosmogenic ^{10}Be, and 20.3 at/g/y (Niedermann, 2000) for cosmogenic ^{21}Ne. Scaling of these production rates to sampling sites was done using the scaling factors given by Stone (2000). Lowering of the local production rates due to sample thickness and geometric shielding is less than four percent. The exact correction factors for each sample are reported in Table 1.

Results

The glacial drift RH 4 is supposed to be older than Late Pleistocene. But when did the ice retreat from RH 4 surfaces, and as a consequence, when did TCN production start? As Table 2 reveals, RH 4 is of pre-LGM age, but no clear age cluster defines the timing of deglaciation. The minimum ^{21}Ne exposure ages (assuming no erosion) vary considerably from 86 ± 15 ka to 951 ± 30 ka. Similarly, surface exposure ages determined with ^{10}Be range from 69 ± 4 ka to 900 ± 54 ka. All errors reported in Table 2 are within 2σ confidence levels. They include errors for the variability of chemical processing for the radionuclide, and statistical, sensitivity, and mass-discrimination errors for the noble gas measurements.

Table 2. Calculated exposure ages.

Sample	Minimum ^{21}Ne age (ka)	Minimum ^{10}Be age (ka)	^{21}Ne age (ka) ε = 35 cm/Ma	^{10}Be age (ka) ε = 35 cm/Ma	^{21}Ne age (ka) ε = 45 cm/Ma	^{10}Be age (ka) ε = 45 cm/Ma
RHS 1	86 ± 15	69 ± 4	88 ± 15	70 ± 4	89 ± 15	71 ± 4
RHS 2	951 ± 30	900 ± 54	1396 ± 44	1423 ± 85	1686 ± 53	1892 ± 114
RHS 3	703 ± 32	678 ± 41	908 ± 41	902 ± 54	1004 ± 45	1018 ± 61
RHP 10	265 ± 16	230 ± 15	288 ± 17	248 ± 16	296 ± 18	254 ± 17

As mentioned in the previous paragraph, ^{21}Ne ages are quite consistent with the radionuclide data. Minimum ^{10}Be and ^{21}Ne ages from the two oldest samples differ by less than six percent. This difference can be explained by continuous erosion that has been active for the whole duration of exposure. Figure 3 shows an erosion island plot, indicating erosion rates of 35 ± 10 cm/Ma for the quartzite RHS 2 and 45 ± 25 cm/Ma for the sandstone sample RHS 3. The effect of such erosion rates on the exposure ages of the sampled erratic boulders can be seen in Table 2. However, the neon and beryllium exposure age differences of the younger samples cannot be explained by erosion, as the data points fall off the erosion island in Figure 3. For RHS 1, the offset is because of ineffective separation of cosmogenic neon from other neon components (Figure 4). This results in an overestimation of the cosmogenic neon concentration, hence in a too old ^{21}Ne age. For RHP 10 – as for the older samples – the neon data presented in Figure 4 plots on the atmospheric-cosmogenic mixing line, demonstrating the cosmogenic origin of the neon excess over air used for age calculation. The discrepancy between the two TCN ages of RHP 10 is, therefore, most probably due to burial of the erratic boulder beneath cold-based ice. Cosmogenic nuclide concentrations of RHP 10 imply a burial period of ~400 ka and a total exposure–burial history (burial age + ^{21}Ne age) of ~665 ka.

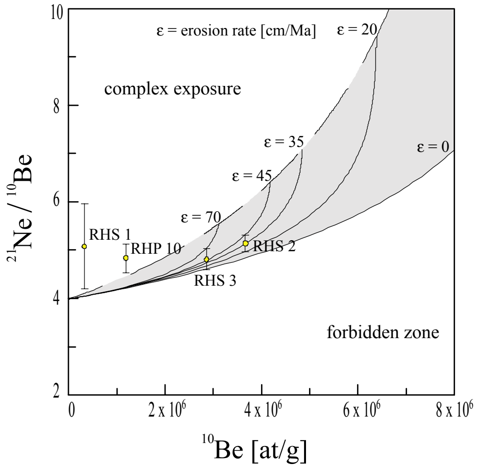

Figure 3. Erosion island plot.

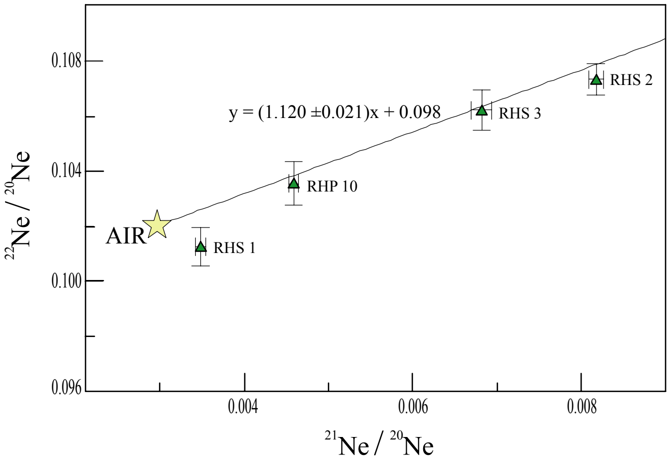

Figure 4. Neon three-isotope plot showing the 600 °C temperature steps, used for age calculation.

Discussion

Our investigation of the RH 4 drift confirms a pre-LGM age of the deposit, but at the same time suggests multiple episodes of glacial deposition. RHS 2 gives evidence of an earlier change of the EAIS surface level that happened about 1.4 Ma ago. Deposits from this glacial event seem to be only locally preserved, because subsequent ice advances possibly reworked other deposits of the same glacial phase. A major ice advance occurred ~1.0 Ma before present, as indicated from the erosion-corrected ages of sample RHS 3. This sample comes from a well-defined erratic alignment of a former glacial lobe margin entering the Ricker Hills from ESE. This geomorphologic evidence represents one of the highest outcrops of RH 4 (about 1590 m asl). Moreover, the consistent isotopic data (^{10}Be and ^{21}Ne) of RHS 3 exclude any relevant burial after, or pre-exposure prior to deposition.

The youngest erratic boulder (RHS 1) was most likely affected by reworking or post-depositional overturning due to periglacial movements of the sub-surface. For that reason its age is insignificant for this study. By contrast, RHP 10 implies that there was a third Pleistocene ice advance that buried parts of the former deposits in the low elevated parts, close to the LGM drift leaving the samples RHS 2 and RHS 3 (at higher elevations) unburied. Such a burial scenario is often observed in polar environments, where landscapes are preserved under cold-based ice (Fabel et al., 2002; Sugden et al., 2005). However, an exact timing of the youngest pre-LGM ice fluctuation is not possible from our data. The result from RHP 10 only leads us to assume that the upper limit for this event is at about 665 ka before present.

Further samples from the area need to be analysed with TCN to confirm the three postulated Middle and Early Pleistocene glacial events. Nevertheless, there is clear evidence of multiple Pleistocene EAIS variations in the Ricker Hills, and that these ice fluctuations were of limited amplitudes of less than 500 m.

Summary

Our study of glacial deposits in the Ricker Hills showed that at least three EAIS variations of limited extent occurred in Early to Mid-Pleistocene time. Cosmogenic ^{10}Be and ^{21}Ne analyses of erratic boulders lead us to suppose, that these ice level changes occurred at ~1.4 Ma, ~1.0 Ma, and <665 ka before present.

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